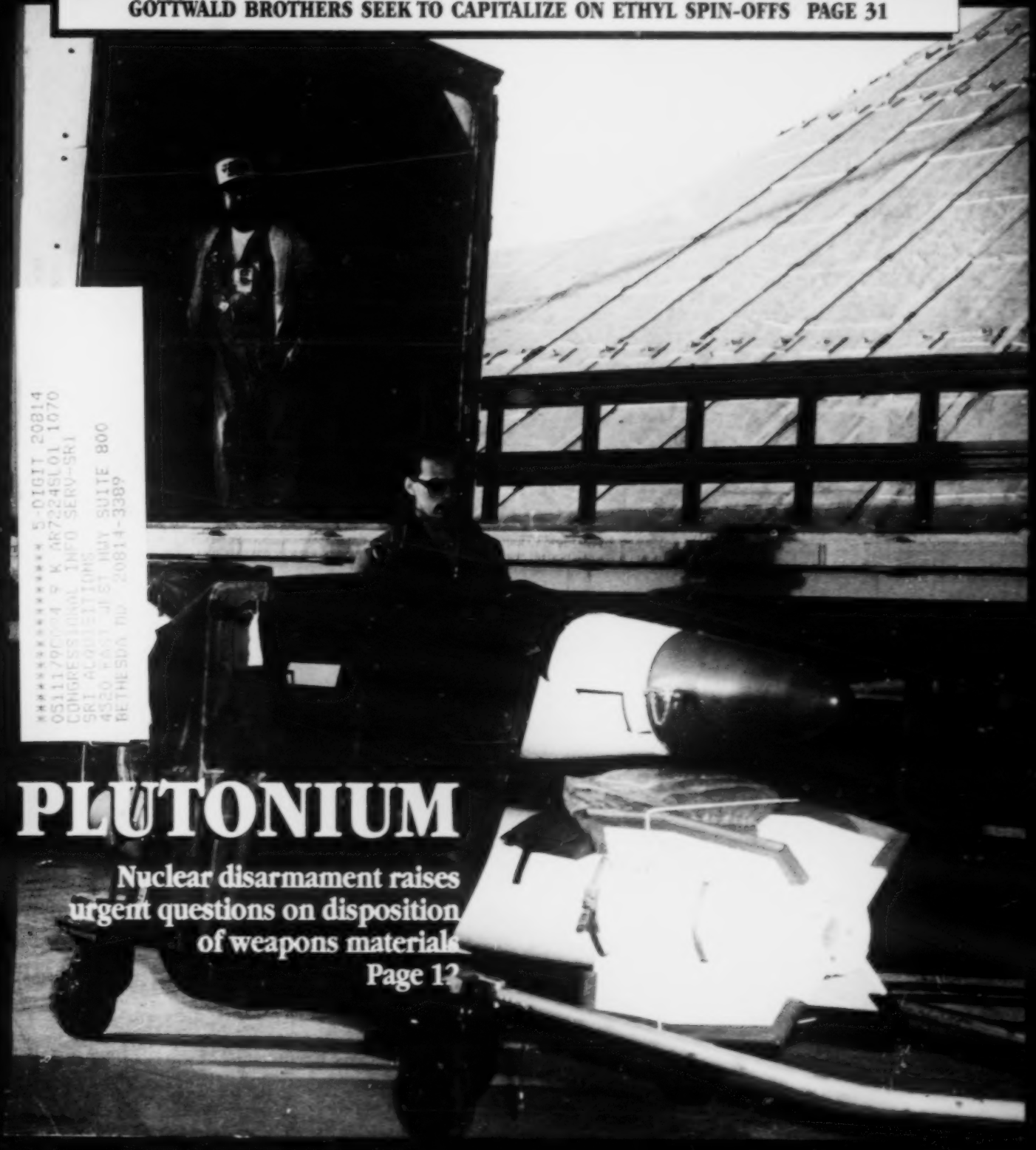
A1250-1

CHEMICAL & ENGINEERING NEWS

C&EN

JUNE 13, 1994

GOTTWALD BROTHERS SEEK TO CAPITALIZE ON ETHYL SPIN-OFFS PAGE 31



********** 5-DIGIT 20814
05117PCCC4 P K AR7224SL01 1070
CONGRESSIONAL INFO SERV-SRI
SRI ACQUISITIONS
4520 EAST WEST HWY SUITE 800
BETHESDA MD 20814-3389

PLUTONIUM

Nuclear disarmament raises urgent questions on disposition of weapons materials

Page 12

CHEMICAL & ENGINEERING NEWS
C&EN
JUNE 13, 1994

NEWS OF THE WEEK

- A detection technique for NMR signals—one that uses mechanical force sensing—provides unprecedented sensitivity and spatial resolution. **Page 6**
- J. T. Baker Inc. is put up for sale by parent Procter & Gamble, the latest in a series of ownership changes in the lab chemicals area. **Page 7**
- Based on two recent discoveries, chemists at the University of South Carolina have begun the first studies of the biological activity of unsubstituted buckminsterfullerenes. **Page 7**
- The "dirty laundry" fight rages on between Unilever and Procter & Gamble over Unilever's popular new detergent formulation for European markets. **Page 8**
- In a novel move to encourage collaboration and dissemination of innovative projects, NSF brought together educators working on NSF-sponsored undergraduate curriculum projects and publishers. **Page 8**
- Planned sale of securities tied to Lyondell stock is postponed by Arco pending completion of investigation into Lyondell's alleged noncompliance with emission regulations. **Page 9**

COVER: Workers transport nuclear bombs in preparation for disassembly and plutonium removal at Department of Energy's Pantex site near Amarillo, Tex.

Volume 72, Number 24
CENEAR 72 (24) 1–56
ISSN 0009-2347

BUSINESS

Bruce and Floyd Gottwald, the two brothers who built Ethyl Corp. into a diversified chemicals firm, position spin-off companies for growth, say splitup will focus investor attention on the value of each company's assets and business. **Page 31**

Biotech company Cytogen and its two-year-old R&D funding vehicle, CytoRad, may be heading toward litigation to sort out disagreements over each other's contractual obligations. **Page 34**

GOVERNMENT

Reauthorization of the Clean Water Act remains in doubt because diverse groups—including chemical industry—object to provisions that address discharges into groundwater as well as unfunded mandates, wetlands designations, and risk assessment. **Page 37**

SCIENCE/TECHNOLOGY

Newly developed catalytic monoclonal antibody catalyzes a cationic cyclization reaction, giving high yield of one specific product instead of a complex mixture of products. **Page 43**

NEWS FOCUS

Disposal of plutonium from dismantled nuclear weapons and in spent nuclear reactor fuel rods is a large, complicated, and urgent problem for the U.S. and Russia. **Page 12**

LETTERS 4
EDITOR'S PAGE 5
CONCENTRATES
Business 26
Government 36
Science/Technology 41
THE DEPARTMENTS
People 54
Newscripts 56

Chemical & Engineering News
1155—16th St., N.W., Washington, D.C. 20036
Editor: Michael Heylin (202) 872-4501
Managing Editor: Madeleine Jacobs
Assistant Managing Editors: James H. Krieger, Janice R. Long, Rebecca L. Rawls, Donald J. Soisson, William J. Storck
Staff Editor: Ernest L. Carpenter
Senior Correspondents: Lois R. Ember, Wilbert C. Lepkowski
News Editor: Richard J. Seltzer
Senior Editors: Northeast News Bureau: Marc S. Reisch, Stephen C. Stinson; Chicago: Joseph Haggin; Washington: Stuart A. Borman, Mairin B. Brennan, Doron Dagani, Bette Hileman, Pamela S. Zurer
Associate Editors: Jane K. Baker, Robin M. Giroux
Service Departments Editor: Linda Romaine Ross
Editing Services: Arlene Goldberg-Gist (Head), Rita E. Johnson (Editorial Assistant), Patricia Oates (Administrative Assistant)
News Bureaus: Northeast: (905) 906-8300 Ann M. Thayer (Head), Elisabeth Kirschner (Assistant Editor), Rachel Eskenazi (Administrative Assistant). Houston: (713) 558-2912 Susan J. Ainsworth (Head). Washington: (202) 872-4495 David J. Hanson (Head). West Coast: (510) 653-3630 Rudy M. Baum (Head), (206) 517-5034 Deborah L. Illman (Associate Editor)
Foreign Bureau: London: (01) 4481 870-6884 Patricia L. Layman (Senior Editor)
Graphics and Production: Leroy Corcoran (Head), Barbara Fryer (Art Director), Linda Mattingly (Staff Artist), Diane Kelly (Costing)
Composition Systems Administrator: Vincent L. Parker. **Assistant:** Robin L. Braverman
Business Manager: Arthur Poulos
Marketing Manager: David Schulbaum
Circulation Manager: Donna W. Carvana
ADVISORY BOARD: Marvin Cassman, Jerry Caulder, P. M. Chakrabarti, Rhetta Q. Davis, Peter B. Dervan, Marye Anne Fox, Richard A. Lerner, Gerald Epstein, Stephen J. Lippard, Peter J. Neff, James N. Pitts Jr., Douglas J. Raber, Bassam Z. Shakhashiri, Harold A. Sorgenti, Kathleen C. Taylor, Margaret A. Tolbert, Charles S. Tuesday, Theodore R. Williams
Published by
AMERICAN CHEMICAL SOCIETY
(202) 872-4600; TDD (202) 872-4432
John Kistler Crum, Executive Director
Robert H. Marks, Director, Publications Division
PUBLISHING BOARD: Joseph A. Dixon *(Chairman); Board of Directors Chairman:* Paul H. L. Walter; *President:* Ned D. Heindel; Paul S. Anderson, Richard L. Deming, Paul W. Jennings, Barbara J. Peterson
Subscription & Member Record Service: Send all new and renewal subscriptions with payments to: ACS, Dept. L-0011, Columbus, Ohio 43268-0011. Correspondence and telephone calls for changes of address, claims for missing issues, subscription orders, status of records and accounts should be directed to: Manager, Member & Subscriber Services, ACS, P.O. Box 3337, Columbus, Ohio 43210; (800) 333-9511 or (614) 447-3776.
For changes of address, include both old and new addresses with ZIP code numbers and mailing label from a recent issue. Allow four weeks for change to become effective. Claims for missing numbers will not be allowed if loss was due to failure of notice of change of address to be received in the time specified; if claim is dated (a) North America: more than 90 days beyond issue date, (b) all other foreign: more than one year beyond issue date; or if the reason given is "missing from files."
Subscription Rates 1994: Printed editions: nonmembers U.S. 1 yr. $115, 2 yr. $207; outside U.S. 1 yr. $152, 2 yr. $281. Air freight rates available on request. Rates above do not apply to nonmember subscribers in Japan, who must enter subscription orders with Maruzen Co. Ltd., 3–10 Nihonbashi 2-chome, Chuo-ku, Tokyo 103, Japan. Tel: (03) 272-7211. Single copies: Current $18. Rates for back issues and volumes are available from Microforms & Back Issues Office, ACS, 1155—16th St., N.W., Washington, D.C. 20036. Back and current issues available on microfilm and microfiche. Rates on request from Microform Program, ACS.
Chemical & Engineering News (ISSN 0009-2347) is published weekly except for the last week in December by the American Chemical Society at 1155—16th St., N.W., Washington, D.C. 20036. Second-class postage paid at Washington, D.C., and additional mailing offices. POSTMASTER: Send address changes to C&EN, Member & Subscriber Services, P.O. Box 3337, Columbus, Ohio 43210. ACS assumes no responsibility for the statements and opinions advanced by the contributors to its publications.
Advertising Management: CENTCOM LTD.
(For list of offices see page 55)
Office of Ombudsman: (800) ACS-5558, No. 5–4
© Copyright 1994, American Chemical Society
Canadian GST Reg. No. R127571347

LETTERS

Science's costs, benefits

Bryan J. Cook wonders whether science really benefits humanity (C&EN, May 16, page 5). He deplores that nobody in C&EN has addressed this issue in the past two years, which leads me to write this letter. He blames science for not eliminating wars, but for invariably creating new dilemmas. Cook quotes Ralph Waldo Emerson, who in 1841 said "society never advances."

Cook could easily avoid the dilemmas that science has created by never using a bicycle or a car; never crossing a metal bridge; and avoiding all medicinals that cure tuberculosis, plague, glaucoma, and high blood pressure. In addition, he should bypass antibiotics, medical care, and all hospitals. He could return to the infant mortality figures during the London plague and the wheat yields per acre of the same year. Not only the dilemmas of electric power and biotechnology, but also the steam engine should be avoided, along with "chemicals," man-made food additives, and purified drinking water.

An excellent book by Paul R. Gross and Norman Levitt, "Higher Superstition: The Academic Left and its Quarrels with Science," recites the many absurdities about science that flow freely from postmodernism, departments of sociology and English, and other nonscientists equally convinced that science does not "really benefit humanity." While these folks all appear to use electric light and take aspirin, they seem secure in the knowledge that these benefits really come from rain forest shamans.

Edwin A. Matzner
St. Louis

Bryan J. Cook's comments are right on target, and he is not alone in his views. During my 39-year career teaching chemistry and chemical engineering at the University of Mississippi, I not only expounded on the basic laws of science and engineering, but I also introduced and emphasized four fundamental laws, which I named for convenient reference.

First, the law of interconnectedness: Everything is connected to everything. Second, the law of diverse effects: Every action results in both advantages and disadvantages. Third, the law of choices and consequences: The freedom to make choices does not include the freedom to choose the consequences of the choices. And fourth, the law of cascading effects: Every action results in an infinite number of cascading effects. That is, every action not only has an immediate or primary effect, but also results in secondary, tertiary, and continuing effects ad infinitum.

Katherine Ann Porter in her book "The Ship of Fools" has one of her characters say (not quoted exactly): "Probably as much harm has been done in doing good as good has been done." Some years ago, ethicist Leon Kass, in an excellent newspaper article on "America and the Future of Man," said in part: "Man's victories have been expensive—it seems that our predicaments are the corollaries of our greatest successes."

When there were fewer people, and they were less concentrated, it may not have made too much difference what was done (that is, it could be tolerated). Today, that is no longer the case. An examination of people's actions through history suggests to me that the net total advantages of a discovery or "advance" are almost balanced by the net total of the disadvantages. Even though people have demonstrated that they have little ability to see into the future, a serious effort must be made to analyze our actions in an attempt to make sure that the net advantages will probably outweigh the net disadvantages. I cringe daily when I see the business-industrial world focusing so much attention on last quarter's "bottom line" and on "downsizing." The world needs more of Cook's thinking.

Frank A. Anderson
Oxford, Miss.

Recently discovered elements

In Darleane Hoffman's periodic table (C&EN, May 2, page 25), the newly discovered elements are shaded in blue. They are Tc (atomic number 43), Pm (61), At (85), Fr (87), Np (93), and all higher atomic numbers. These elements are all man-made, or are present in Earth's crust in extremely low amounts because they are very unstable.

The differences between their atomic numbers form an intriguing pattern,

$61 = 43 + (2 + 6 + 10)$
$85 = 43 + (2 + 6 + 10) + (\quad 10 + 14)$
$87 = 43 + (2 + 6 + 10) + (2 \quad + 10 + 14)$
$93 = 43 + (2 + 6 + 10) + (2 + 6 + 10 + 14)$

since the integers that you need to add to relate Tc to the rest are the same as the numbers of electrons in closed electron shells (s^2, p^6, d^{10}, f^{14}).

This is presumably a coincidence because I know of no relationship between nuclear stability and electronic configurations. Or could there be?

Peter J. Sadler
London

Authorization to photocopy any article for internal or personal use beyond the fair use provisions of the Copyright Act is granted by ACS to libraries and other users registered with the Copyright Clearance Center (CCC), provided that the fee of $3.00 per article copy is paid directly to CCC, 222 Rosewood Dr., Danvers, Mass. 01923, USA. Copying for other than internal or personal use without express permission of ACS is prohibited. Address requests for customized bulk reprints to ACS Copyright Administrator, 1155—16th St., N.W., Washington, D.C. 20036, or call (202) 872-4367. The CCC Code for C&EN is 0009-2347/94 $3.00.

U.S. And Russia Face Urgent Decisions On Weapons Plutonium

Possibility of terrorist diversion, outright theft drive move for new safeguards, choice of optimum disposal methods

Bette Hileman, C&EN Washington

The current international crisis involving North Korea's possession of plutonium—possibly enough to make one or two nuclear weapons—is coming at a time when the U.S. and Russia are worrying over what to do with all the plutonium they remove from their declining nuclear arsenals.

At the heart of the issue is the radioactive silvery metallic element named after the planet Pluto. Its primary danger lies in its fissionability with neutrons to yield atomic energy, and thus its use in nuclear weapons. Although the element occurs in nature only in minute quantities, plutonium is created in the uranium fuel rods of nuclear reactors. Accumulating amounts of plutonium from the world's nuclear power plants, as well as increasing stores of plutonium from dismantling nuclear weapons, have created a quandary for humankind.

It's become painfully clear that although nuclear disarmament offers great hope for improving world security, it also involves serious risks, not the least of which is the disposition of the radioactive isotopes used in nuclear weapons. With the end of the Cold War, the U.S. and Russia have agreed to drastic reductions in the number of nuclear weapons they possess. Thousands of warheads have already been removed from delivery systems, and many have been dismantled, meaning that the fissile materials—highly enriched uranium and plutonium—have been taken out. By 2003, a total of 40,000 weapons may have been dismantled, leaving about 5,000 on each side. In the process, as much as 150 metric tons of plutonium will be removed from the weapons.

This surplus plutonium poses a "clear and present danger to national and international security," warns a National Academy of Sciences (NAS) study released in January, titled "The Management and Disposition of Excess Weapons Plutonium." Indeed, it poses a threat at least as great as the one posed by North Korea's possession of a relatively small supply of plutonium.

In many respects, fissile materials outside warheads pose more security problems than those in intact weapons. As long as such materials are contained within weapons, they are heavily guarded by the military complexes on each side. Once they are removed, they are not necessarily under such control—unless they are being reserved for future military use.

For countries or terrorists who want to manufacture nuclear arms, the stumbling block is obtaining the fissile materials. It is very expensive and technologically demanding to set up facilities to make highly enriched uranium or to build nuclear reactors and reprocess the spent fuel to produce plutonium. On the other hand, it is relatively simple to design and build the hardware for a crude weapon. The danger is real, therefore, that weapons-grade uranium or plutonium not under tight security could be stolen either by terrorists or by thieves who would profit from selling it to renegade countries.

In actuality, weapons-grade uranium does not have to pose much of a threat. Diluting the highly enriched uranium with uranium-238, the main constituent of natural uranium, to make economical reactor fuel is a straightfoward process. Subsequent reenrichment of the fuel for use in weapons is very unlikely because it demands sophisticated isotope separation techniques few countries have developed. Plutonium is another matter. All of its isotopes are fissile, so isotopic dilution does not render plutonium unusable for weapons.

Over the past few years, many different methods of disposing of plutonium have been proposed. They range from shooting it into the Sun with missiles, to deep-seabed disposal, to fissioning it within a new generation of nuclear reactors. The NAS report rejects most of the methods suggested so far, but does recommend pursuing two of the options. One is to incorporate the plutonium in mixed-oxide fuel, a mixture of plutonium and uranium oxides, and use it to fuel commercial nuclear reactors. The other is to mix the plutonium with high-level waste and molten glass and mold the resulting material into large glass logs for eventual geologic disposal.

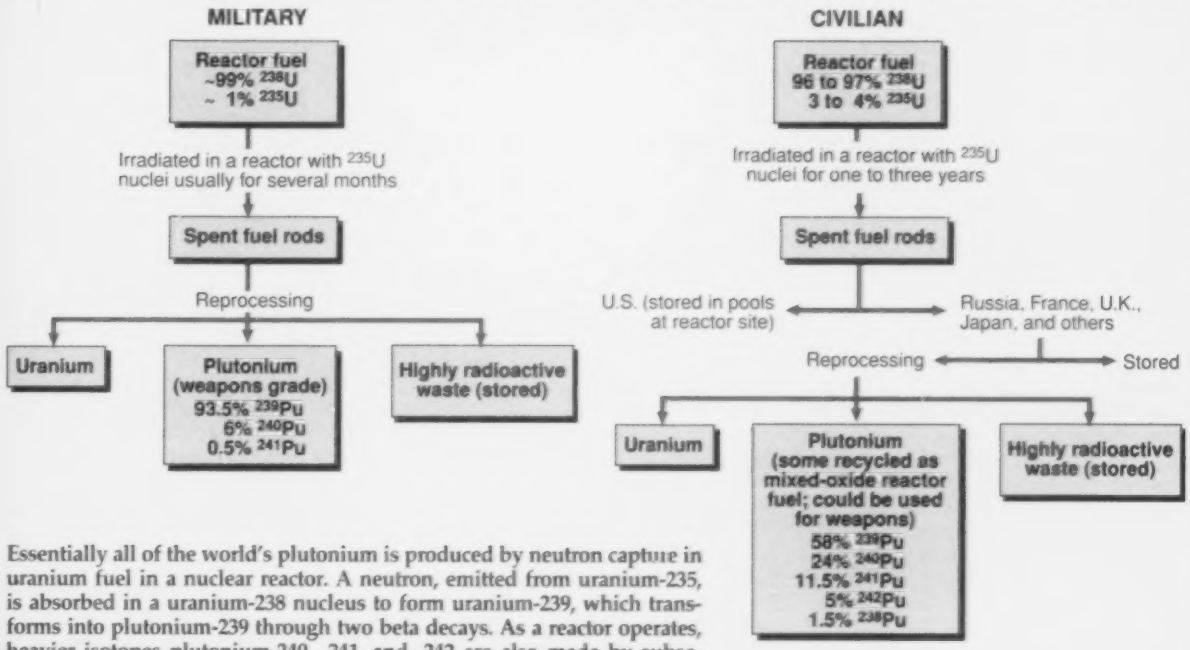
One troubling difficulty is that although the options for plutonium disposal recommended by the NAS report could work in the U.S., they may not only be unacceptable in Russia, but also unwise and unworkable given safety problems with its reactors and the breakdown in infrastructure.

Until recently, neither the U.S. nor Russia has had to seriously consider how they were going to safely store or dispose of large amounts of surplus plutonium. And so far, neither country is anywhere close to reaching a consensus on the issue, though the Clinton Administration is planning to make a decision by 1996.

Basically, the conflict is between those who believe plutonium will have no value in the near future and those who believe it has intrinsic energy value that can be exploited within a few decades. The latter group expects the plutonium will be useful as fuel for breeder reactors or some other kind of advanced nuclear reactor.

John H. Gibbons, director of the White House Office of Science & Technology Policy (OSTP), recently expressed the Ad-

Plutonium for military and civilian purposes is produced by essentially the same process



Essentially all of the world's plutonium is produced by neutron capture in uranium fuel in a nuclear reactor. A neutron, emitted from uranium-235, is absorbed in a uranium-238 nucleus to form uranium-239, which transforms into plutonium-239 through two beta decays. As a reactor operates, heavier isotopes plutonium-240, -241, and -242 are also made by subsequent neutron capture. The longer the fuel stays in the reactor, the higher are the concentrations of heavier isotopes. If weapons-grade plutonium is being produced, the fuel is usually removed after a few months. If the reactor is being run primarily to produce power, the fuel is left in the reactor for up to a few years. In the U.S., waste from military reprocessing will be mixed with molten glass, made into glass logs, and eventually stored in a geologic repository. Spent fuel rods from civilian reactors will also be stored in a geologic repository after one is approved. In the countries that reprocess spent fuel from civilian reactors, part of the extracted plutonium is made into mixed-oxide fuel, a mixture of plutonium and uranium oxides.

ministration's view of how nuclear dismantlement should progress: "Our vision is of the U.S. and Russia running our nuclear weapons complexes in reverse—dismantling thousands of nuclear weapons rather than building more, getting rid of nuclear weapons materials rather than producing ever larger stockpiles, cleaning up rather than further fouling our nuclear sites, fostering openness and trust rather than maintaining strictest secrecy. This Administration is committed to making that vision a reality."

And it needs to do so soon. In the U.S., weapons are being dismantled at a rate of about 1,800 annually at the Department of Energy's (DOE's) Pantex plant near Amarillo, Tex. By 2003, up to 400 metric tons of highly enriched uranium and about 50 metric tons of plutonium will have been taken from weapons. In Russia, roughly the same number of weapons are being dismantled each year at four sites. Eventually, the Russians will remove more than 500 metric tons of highly enriched uranium and 50 to 100 metric tons of plutonium from their warheads.

Deteriorating safeguards

Experts agree that though security could be improved, plutonium and highly enriched uranium are being guarded reasonably well in the U.S. But in the former Soviet Union, where the political and economic situation is unstable and organized crime has skyrocketed, the risk of theft or diversion is high. The system of accounting for weapons and fissile materials was never sophisticated, but those materials were heavily guarded before the breakup of the Soviet Union. Now, workers at the nuclear storage and research facilities are paid infrequently or not at all. The temptation to accept bribes or to sell weapons-grade plutonium or highly enriched uranium is great. To compound the problem, substantial quantities of fissile materials are located in four former Soviet countries: Russia, Ukraine, Kazakhstan, and Belarus.

Already, three thefts of uranium, including one of weapons-grade material, have been confirmed in Russia. Also, according to Vladimir A. Orlov, a journalist with *Moscow News*, several plutonium thefts took place at Krasnoyarsk-26, a formerly secret city near Krasnoyarsk in Siberia, but the thieves were caught. In addition, organized crime is spreading across Europe from Italy into Russia, and many people fear it may soon get into the business of smuggling plutonium and enriched uranium from Russia. First deputy minister of the interior Mikhail Yegorov says there are nearly 5,700 criminal groups in Russia with a total of about 100,000 members and connections in 29 countries. Yegorov's agency investigated nine alleged thefts of fissile weapons materials during the past 18 months. The U.S. Federal

Nuclear weapons can be made from reactor-grade plutonium

In its report, "The Management and Disposition of Excess Weapons Plutonium," a National Academy of Sciences (NAS) panel states that nuclear bombs can be made from spent fuel from ordinary nuclear power plants.

That statement directly contradicts the nuclear power industry's long-standing assertion that bombs could not be made from its spent fuel. In fact, just recently, the Japanese government-owned utility, the Power Reactor & Nuclear Fuel Development Corp., made this assertion in a promotional video it distributed to reassure citizens living near the Monju breeder reactor, which started operating in April.

Some nuclear power advocates admit that nuclear weapons could be manufactured with reactor plutonium. The U.S. government did, after all, build and test a bomb made of commercial reactor-grade plutonium in 1962. However, advocates claim that since no country has actually chosen to do so, reactor plutonium is not strategically important.

According to the NAS panel, bombs made from reactor plutonium, while somewhat less efficient and less reliable than those made of the weapons-grade material, can still be highly destructive. If a reactor is used to produce plutonium for weapons, fuel rods are removed from the reactor early in the radiation cycle, when the ratio of plutonium produced from uranium-238 absorption of a neutron and decay to plutonium is about 93% plutonium-239 to about 6% plutonium-240. If a reactor is used for power production, the fuel rods are left in the reactor much longer to extract more of their energy potential and larger amounts of the higher isotopes of plutonium are created. Typically, when the spent fuel is removed, about 58% of the plutonium is plutonium-239, 24% is plutonium-240, and the rest is mostly plutonium-241 and americium-241.

As a nuclear weapon is detonated, the plutonium is compressed using chemical explosives and, at a precise moment, a burst of neutrons is generated to set off a chain reaction. However, if the plutonium used to make a bomb is contaminated with higher than normal percentages of plutonium-240 or -242, the spontaneous neutrons they emit have a high probability of setting off the chain reaction a fraction of a second too early, reducing the bomb's yield.

But even if preinitiation occurs at the worst possible moment, a simple bomb made of reactor-grade plutonium would have a yield of one to a few kilotons, enough to cause at least one third of the destruction wrought by the Hiroshima weapon, says Brian G. Chow, senior physical scientist at Rand Corp., Santa Monica, Calif.

Another drawback of reactor-grade plutonium is that it is too hot. It generates six to 10 times more heat per kilogram than does weapons-grade plutonium. So a bomb made of reactor plutonium would have to be constructed in such a way that heat is conducted away from the plutonium while the bomb is in storage, or it would need to be assembled only shortly before use.

Since weapons can be made of reactor plutonium, the NAS panel recommends that the "U.S. pursue new international arrangements to improve safeguards and physical security over all forms of plutonium [including that in spent fuel] and highly enriched uranium worldwide."

All forms of plutonium should eventually be placed under International Atomic Energy Agency safeguards, says John P. Holdren, chairman of the Committee on International Security & Arms Control that conducted the NAS study and professor of energy at the University of California, Berkeley. "The adequacy of protection and safeguards for separated civilian plutonium deserve a searching review," he says.

Bureau of Investigation will soon open a Moscow office to work with the Russians on preventing thefts of nuclear weapons and materials.

"Every day that goes by, every weakening of the basic custodial and control arrangements in the former Soviet Union adds risks that fissile materials may be stolen and wind up in the hands of potential proliferators," says Catherine M. Kelleher, senior fellow in the foreign policy studies program at the Brookings Institution in Washington, D.C.

Wolfgang K. H. Panofsky, professor and director emeritus of the Stanford Linear Accelerator Center, Stanford University, and chairman of the panel that wrote the NAS study, echoes her view: "Any day now, we could wake up and read in the morning newspaper that enough material for a dozen bombs really has been stolen. . . . On our last visit to Russia a couple of months ago, we were told universally that their safeguarding of nuclear materials had deteriorated. But we still don't have a very good way to quantify that."

Since an economical fuel can be made from uranium removed from weapons, almost no one suggests it be put into irretrievable storage or made into a form that can't eventually be used to power nuclear reactors. The U.S. has contracted to purchase 550 metric tons of highly enriched uranium from the Russians for $12 billion over the next 20 years.

Unlike uranium, plutonium does not have current economic value for generating electricity. Twenty years ago, most experts believed this radioactive, synthetic element could eventually be substituted for uranium-235 in conventional nuclear reactor fuel and put into mixed-oxide fuel. This mixture, they thought, would be an economical fuel for nuclear reactors. At the time, nuclear power was expected to expand rapidly, and uranium was predicted to be in short supply soon. Now, many more sources of uranium have been discovered and nuclear power's expansion has slowed.

Today, even if the plutonium is free, mixed-oxide fuel costs $500 per kg more than conventional uranium fuel, which costs about $1,000 per kg. This extra cost makes electricity generated with mixed-oxide fuel more expensive. And most experts believe it will not be an economical fuel for many decades. "We are talking basically about a half century" before plutonium becomes competitive, says Panofsky.

Recommended disposal methods

The panel that wrote the NAS study is a standing committee called the Committee on International Security & Arms Control. It suggests steps that should be taken now to guard supplies of plutonium removed from weapons. One

step is bilateral U.S.-Russian monitoring of warhead dismantlement. Others include setting up secure interim storage for the fissile materials and establishing an international monitoring system to verify the stockpiles and ensure that materials are not withdrawn for use in new weapons. The panel also urges Russia to stop producing fissile weapon materials and both countries to commit a very large fraction of their plutonium and highly enriched uranium from dismantled weapons to nonaggressive uses. The U.S. and Russia have already made initial moves to accomplish these goals but have not fully implemented any of them.

After these steps are taken, the NAS committee recommends that plutonium be disposed of by one of its two suggested options. If plutonium is made into mixed-oxide fuel, it should be burned in one or several reactors that are owned or controlled by governments. These could be light-water reactors in the U.S. and Russia, or heavy-water-moderated reactors in Canada. In the process, about 30% of the plutonium would be destroyed and the rest embedded in spent fuel. In that form, it would be far less accessible as a source of weapons material than are the hollow metal-clad plutonium spheres—pits—contained in weapons that are now being stored in the U.S. Once the project has begun, burning plutonium as mixed-oxide fuel would cost the U.S. government from one to several billion dollars over 10 years, but that amount is reasonable considering the danger these stockpiles pose, Panofsky says.

The other option, mixing weapons plutonium with high-level nuclear waste and molten glass and molding this mixture into 2-metric-ton stainless-steel-clad glass logs, would probably cost less than burning plutonium as mixed-oxide fuel, says Richard L. Garwin, IBM fellow emeritus at Thomas J. Watson Research Center in Yorktown Heights, N.Y. The glass log option is attractive in some ways because it is only a minor modification of what DOE intends to do anyway. The agency will soon be mixing high-level waste from weapons production with molten borosilicate glass and molding this into logs at its Savannah River facility. If the glass log option is used, the plutonium would be put in along with the waste.

Although spent fuel and the logs would contain plutonium, thieves would be less likely to steal them because they would be heavy and so radioactive as to require remote handling. A person cannot stand a few feet from fresh spent fuel or a log for more than a few minutes without danger of serious injury. Both the spent fuel from burning plutonium in mixed-oxide fuel and the glass logs would eventually be disposed of in a geologic repository. However, neither disposition option could begin to make a dent in the nuclear stockpile in less than a decade, so plutonium pits would still have to be guarded carefully for many years to come.

The panel also mentions a third option, which it says may be "comparably attractive": burying the plutonium in 4-km-deep boreholes sealed with bentonite clay and concrete. Plutonium in a borehole would be very inaccessible to would-be weapons makers, but it could be recovered at a later time by the state.

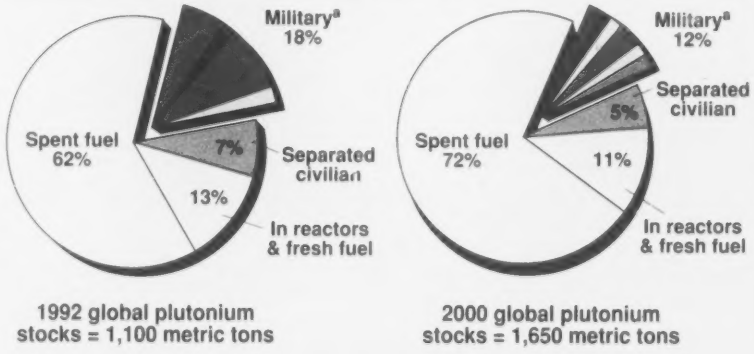
Taken together, these immediate and intermediate steps to secure plutonium would guard against three contingencies in the former Soviet Union—breakup, breakdown, and breakout, Panofsky says. He defines breakup as the creation of several nuclear armed states where previously there was only one, breakdown as the erosion of control over nuclear materials, and breakout as the repudiation of arms reduction agreements and rebuilding of a large nuclear arsenal.

Unlike many previous NAS studies, this one on plutonium disposition is strongly influencing U.S. policy. The panel's proposals now form the foundation of the Administration's thinking on the issue. However, the situation is still fluid, and a different disposition path than any of those recommended by NAS may eventually be chosen. "We are examining a variety of other disposition options as well," says Gibbons.

Harold A. Feiveson, a research scholar at Princeton University, offers another such disposition option, a compromise between those who want to save plutonium for a new generation of reactors, as the Russians do, and those who want to make it inaccessible in the near future—the U.S. position. He suggests that the Russians mix plutonium in their pits with molten glass and mold this into 2-metric-ton logs. These could be stored indefinitely. They would not be highly radioactive, but they would be a lot harder to steal than a pit, which contains on average 3 to 4 kg of plutonium.

The Russians might be inclined to accept this idea because it would allow them to extract the plutonium at a future time for use in reactors. Another possibility is to blend plutonium into a uranium dioxide-based matrix obtained by exposing spent fuel to high-temperature oxidation-reduction cycles, say Feiveson and Ed Lyman, a research

Military uses account for small and declining fraction of world plutonium stocks



Note: The amount of plutonium in the weapons of the other nuclear states is very small and is not included.
Source: C&EN estimates based on data from National Academy of Sciences Committee on International Security & Arms Control

physicist, also at Princeton. This would produce dirty (radioactive) mixed-oxide fuel rods that could be stored and, in principle, used later directly in reactors.

Others have suggested that the U.S. purchase the Russian pits just as it is paying $12 billion for Russian highly enriched uranium. "I believe that even though plutonium has negative value to the civil sector," says IBM's Garwin, "it would be worthwhile for the U.S. to buy the weapons plutonium from the Russians at the same price we are paying for highly enriched uranium."

NAS disposal criteria

The NAS panel used several criteria in assessing possible plutonium disposal options: timeliness of implementation, safety, cost, and inaccessibility. First, the panel decided an option should require little or no technological development before it is implemented. Burning plutonium as mixed-oxide fuel meets this criterion fully. Such fuel is being produced at a facility in Belgium, and it has been used successfully to generate electricity in several types of conventional light-water reactors. The glass log option would require a few years of research before it could be implemented.

Worldwide, civilian stocks of plutonium are several times larger than military stocks and growing much faster, by some 60 to 70 metric tons each year. About 80 to 90 metric tons of civilian reactor-grade plutonium is now stored in separated form in various countries, and about 600 metric tons of plutonium is contained in the spent fuel from civilian power reactors. Therefore, the NAS panel concluded that the preferred options should meet what it calls the "spent fuel standard"—making the plutonium from dismantled weapons only as difficult to extract and steal as the plutonium in civilian spent fuel.

The mixed-oxide fuel option would destroy about 30% of the weapons plutonium and embed the rest in spent fuel; the glass log option would not destroy the plutonium but it would make it as difficult to retrieve as is the plutonium in spent fuel.

In addition, the NAS committee wants the plutonium to be disposed of in a way that does not disperse it widely in society. For this reason, it rejects the idea of burning the plutonium as mixed-oxide fuel in a large number of commercial power reactors scattered across the U.S. and Russia. This would provide too many opportunities for theft. "It is important to use only a few reactors and that they be government-owned" to avoid proliferation risks, comments John P. Holdren, chairman of the NAS committee and professor of energy at the University of California, Berkeley.

The deep-borehole option meets most of the panel's criteria except for inaccessibility and, to some degree, development time. The panel believes, however, that since the public has not yet accepted geologic repositories for spent fuel or high-level waste, it would be very reluctant to accept deep-borehole disposal. Also, the borehole method would require further study to determine the risk of plutonium or its decay products being released from the borehole into the environment at some future time.

Technological development

The NAS panel recommends that a choice of disposition options not be made immediately because some technical questions concerning the glass log option need to be answered first. "In the path toward final disposition, there are some very challenging chemical and chemical engineering problems. Those problems that remain to be solved are an important reason why we can't make a technical decision today," says Robert J. Budnitz, president of Future Resources Associates in Berkeley, Calif., and a former member of the Nuclear Regulatory Commission (NRC).

First, scientists do not know what percent of plutonium can be put into glass without causing a criticality problem (a chain reaction) in the melter. Most experiments on glass logs at DOE's Savannah River plant have been done with high-level radioactive waste alone, not with waste plus plutonium.

Plutonium causes concern because it tends to form pockets of locally concentrated material in glass, says Thomas H. Pigford, professor of nuclear engineering at the University of California, Berkeley, and a member—along with Budnitz—of an NAS panel on reactor-related options for the disposition of excess weapons plutonium. "That has been the cause of some nuclear criticality events at Los Alamos," he explains. If it turns out that the glass logs can contain only 1% plutonium, then that option becomes too expensive because of the large number of logs that would have to be made and stored. For the glass log method to be viable, a plutonium content of 3 to 7% would be required. "I couldn't tell you whether we can put enough plutonium in the glass to make vitrification actually sensible," observes Budnitz.

C&EN staff photos

From left, Pigford: security loose at Russian reactors; Holdren: need to minimize opportunities for theft; Panofsky: theft threat is real

The highly enriched uranium deal is only a partial solution

The U.S. deal to buy surplus, highly enriched uranium from Russia is only a partial solution to the problem of uranium proliferation. As part of the deal, the Russians will dilute 550 metric tons of the highly enriched uranium from their dismantled weapons (more than 90% uranium-235) with uranium from ore (mostly uranium-238) so it contains 4.4% uranium-235. The U.S. will purchase the diluted uranium over a period of 20 years for $12 billion. The deal's objectives are to assist the Russian economy, help fund Russia's disarmament, and ensure that the once highly enriched uranium is virtually useless for weapons.

Despite these advantages, the arrangement has several pitfalls. First, the U.S. does not know what fraction of Russia's total stock of highly enriched uranium it is purchasing. The Russian Minister of Atomic Energy, Viktor N. Mikhailov, said recently that Russia had produced 1,250 metric tons. Other Russians say the actual production was 900 metric tons and allege that Mikhailov doesn't know what he is talking about. Oleg Bukharin, a Russian scientist working at Princeton University, calls the amount of highly enriched uranium in Russia "the greatest mystery." But, he says, "My sense is that the 550 metric tons the U.S is buying is most of the surplus."

Furthermore, according to Thomas B. Cochran, senior scientist at the Natural Resources Defense Council, in Washington, D.C., "The protocol worked out by the Administration may permit the U.S. to confirm that the uranium is highly enriched uranium, but it aparently does not permit the U.S. to confirm that the highly enriched uranium actually is [coming] from dismantled weapons."

Another problem is that Russia will sell only a relatively small fraction—about 50 metric tons—of its highly enriched uranium to the U.S. during the next five years. So the bulk of the uranium could remain in Russia in undiluted form for years. During this time, it could present even more of a proliferation risk than plutonium.

It is easier to make a uranium-235 bomb than a plutonium bomb because a simple, gun-assembly design like that used in the Hiroshima weapon (which was not tested before it was used) can be employed. In this type of bomb, two subcritical masses of highly enriched uranium are propelled together with a conventional explosive, producing a supercritical mass—a mass that is more than large enough to sustain a chain reaction.

In contrast, plutonium requires the more complicated implosion technique, which uses a peripheral charge of chemical high explosive to compress the metal. "Plutonium is so tricky, it requires a lot more finesse," says Thomas H. Pigford, professor of nuclear engineering at the University of California, Berkeley, and a member of the National Academy of Sciences panel on reactor-related options for the disposition of excess weapons plutonium.

The situation is much the same in the U.S. There isn't much of an economic incentive for the U.S. to blend down its own supply of weapons uranium for use in power reactors; there isn't any market. And currently, a worldwide uranium glut exists owing to the nuclear power industry's snail-like expansion.

Thus, a lot of unblended, highly enriched uranium that could possibly be stolen by terrorists could also remain in the U.S. for many years. However, the proliferation problem could be solved fairly quickly, if the two governments decide to act. All they would have to do is blend down all the weapons uranium to a ^{235}U enrichment level of 20% or less—a level unsuitable for weapons.

Also, researchers need to determine how glass logs would age in a geologic repository. Over a short time in geologic terms, the boron in the borosilicate glass would act as a neutron absorber. But over perhaps 20,000 to 100,000 years, the boron might leach out preferentially because it is more soluble in water than plutonium, Pigford says, so in some future era, there is a chance the plutonium in the log would become critical.

Budnitz estimates it would take four to six years of research to answer the technical questions about glass logs. "Nevertheless, there is a huge enthusiasm for vitrification in some quarters, because rather rapidly and without using reactors it could dispose of plutonium," he says.

Using the plutonium as mixed-oxide fuel in reactors would require no further research. Some reactors are more suited to burning such fuel than others, however. Most of the existing light-water reactors in the U.S. could not burn a full core of mixed-oxide fuel. Two thirds of the core would have to be conventional uranium fuel unless the reactors were modified with more control rods. There are few U.S. reactors, other than three System-80 light-water reactors at the Palo Verde site in Arizona, that could operate with full mixed-oxide fuel cores without modification.

In Russia, only the VVER-1000 light-water reactors would be safe enough, with some modifications, to burn mixed-oxide fuel. Several VVER-1000s still under construction could be completed in such a way that they could handle full cores.

Technologically, the most inherently suitable type of reactor for burning such fuel is the Canadian deuterium-uranium reactor (CANDU), which is moderated by heavy water and was originally designed with extra neutron control absorbers for the possible future use of plutonium. Consequently, these reactors can handle a full mixed-oxide core with no modification. "Of all the reactor-related options, to me, CANDU is the most attractive," Pigford says. Canada, however, has a long-standing policy against using fuels other than natural uranium in its power reactors. So it is a question of whether Canada could be convinced to contribute to disarmament by burning U.S. or Russian plutonium.

Even some experts who favor burning plutonium in U.S. light-water reactors have misgivings about using the same disposal method in Russia. Because Russian control over its nuclear materials seems to be deteriorating, they worry that plutonium removed from weapons might be stolen as it is being transported to one or several sites to be made into fuel, and they are also concerned about it being stolen from reactor sites.

In addition, they worry about safety problems at even the safest of Russia's light-water reactors, the VVER-1000s, which do not fully meet Western safety standards. For example, with U.S. reactors, two independent supplies of electricity are required so if one fails, the other does not. Russian reactors often have something that looks like two independent systems, but when examined in detail, it turns out they are interconnected. "If one fails, the other one fails," Pigford says.

Management concerns are also an issue. A well-designed, well-built reactor can be run in an unsafe manner. "Recently, I walked into one of [Russia's] nuclear power plants north of Moscow, and it was like going into a supermarket," Pigford recalls. "You go in through a turnstile and there is no careful determination of who you are." Only a handful of people were guarding the reactor in contrast to U.S. plants, which typically have a security force of about 100 people. Management is an issue with glass logs, as well. "Russia has been very careless in its management of environmental controls in reprocessing. Unless they change their ways, I wouldn't want them to go into glassmaking," Pigford says.

Some experts are also concerned that if Russia were to burn weapons-grade plutonium in its light-water reactors, there would be no way to prevent it from reprocessing the spent fuel. Russia currently reprocesses part of the spent fuel from its power reactors.

Because of these concerns, several observers who favor burning plutonium in U.S. reactors say they are opposed to Russia's burning plutonium in its reactors. "There is probably only one thing worse than storing pits in Russia [that are] right now under lock and key," says a Pentagon official, "and that is throwing the pits into oxide production and fuel fabrication and then ultimately reprocessing. We won't be able to control Russian reprocessing. That would just increase [nuclear] proliferation risk, not decrease it."

Advanced reactors suggested

Many engineers at DOE and at several companies that build nuclear reactors are advocating development of advanced reactors for burning weapons-derived plutonium. Basically, they propose using one of four types: advanced light-water reactors, modular high-temperature gas-cooled reactors, advanced liquid-metal reactors (essentially advanced breeders), and accelerator-based conversion.

Of these, the advanced light-water reactor is the closest to commercialization. One such design, the System-80+ reactor developed by ABB-Combustion Engineering, burns a full core of mixed-oxide fuel. It has more safety features than existing light-water reactors, and NRC is well along in reviewing its design. Although this reactor may be safer than existing light-water models, it would not process plutonium any faster per unit of power produced than current reactors.

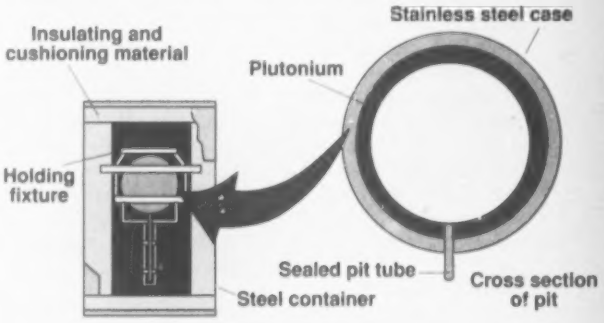
The modular high-temperature gas-cooled reactor is cooled by high-temperature helium and moderated with graphite blocks in the core. It is fueled with tiny pellets of plutonium or highly enriched uranium that are coated with several layers of protective materials, bonded into fuel rods, and placed in the graphite blocks. The reactor can potentially destroy up to 80% of the plutonium in the fuel.

DOE concludes in its 1993 report, "Plutonium Disposition Study," however, that this reactor is the least cost-effective of the five reactors it evaluated. But the manufacturer, General Atomics, says the reactor is actually much more economical than DOE calculates. General Atomics has signed an agreement with the Russian Ministry of Atomic Energy (MINATOM) to develop this reactor jointly for burning Russian weapons plutonium if the U.S. government funds its project.

A number of countries are developing advanced liquid-metal reactors, which recycle and reprocess plutonium. U.S. designs employ a pyroprocessing approach that reduces costs and wastes from reprocessing and never fully separates the plutonium in a form that can be used for nuclear weapons. If plutonium were repeatedly recycled through the reactor, most of it could be fissioned. A more practical approach would be to burn the weapons plutonium in a once-through mode and thus transform it into spent fuel. The capital cost of the advanced liquid-metal reactor is higher than that of light-water models, and the NRC licensing process for it has not advanced very far.

DOE engineers have been developing the accelerator-based conversion reactor both as a means of disposing of weapons plutonium and of fissioning actinides (transuranic elements) and fission prod-

Plutonium from U.S. weapons is contained,



Following removal from a nuclear weapon, the hollow stainless-steel-clad spherical component containing on average 3 to 4 kg of plutonium, commonly referred to as the pit, is placed inside a holding fixture. This holding fixture rests inside a steel container that is insulated and cushioned with a material made largely of cellulose. The assembly is then stored inside a bunker at the Department of Energy's Pantex plant near Amarillo, Tex. (at right).

Johnson: Pantex facility is simple, sound

ucts to reduce the long-term radioactivity of high-level waste.

The neutrons in the accelerator-based conversion system, which are produced by a beam of particles from an accelerator hitting a target, cannot sustain a chain reaction without outside input. This is a safety advantage because the reactor can be shut down instantaneously by turning off the power to the outside neutron source. The fuel is fluid and continuously fed out of the reactor, reprocessed to remove fission products, and fed back in. In the process, plutonium is almost totally destroyed.

Some DOE experts say this reactor would be especially beneficial because it would destroy the plutonium almost completely and reduce the radioactivity of the resulting waste below what it would be with other methods. For example, Edward D. Arthur, project leader for accelerator systems at Los Alamos National Laboratory, claims that accelerator-based conversion could "reduce the long-term toxicity of existing defense wastes destined for a geologic repository." As a result, more waste could be stored in the proposed Yucca Mountain repository in Nevada, he says.

So far accelerator-based conversion exists only on paper, and many technological hurdles remain before this system could be used. But Arthur believes a full-scale demonstration plant could be finished in 15 years. In contrast, Pigford says, accelerator-based conversion could not be developed to destroy plutonium for decades. In its report on this subject released last December, the General Accounting Office agrees with Pigford. It concludes that practical application of this system "is at least decades away, and a number of constraints could slow or prevent application should it be actively pursued. . . . The research necessary to prove that these concepts are technically and economically feasible has not been done."

Pigford also says that reducing the radioactivity of the waste to be stored potentially at Yucca Mountain may not be a real advantage for two reasons. Yucca Mountain's capacity was a political decision, not a technological one, and four or five times as much waste could be stored there, even without decreasing its radioactivity. Furthermore, Pigford says, reducing heat in high-level waste by lowering its radioactivity could create a problem. Right now, waste to be stored in Yucca Mountain would be so hot it would keep any water in its vicinity in vapor form. If the temperature of the waste is reduced, water could remain in liquid form and cause more corrosion.

Many scientists and engineers see the need to dispose of weapons-derived plutonium as a way to increase government funding for the advanced reactors they have been working on. They think that such increased funding would eventually revitalize the nuclear power industry in the U.S. But Panofsky says: "U.S. interests would be served well if one could unlink the decision about the plutonium question from the nuclear power future as much as possible." He and many other nuclear experts also argue that plutonium from weapons is not needed for advanced reactors. If they are developed someday, these reactors could initially be fueled with reprocessed reactor plutonium. It would take a minimum of two decades to develop and license any type of advanced reactor, Panofsky predicts.

The NAS panel therefore rejects the idea of using advanced reactors for burning plutonium. "Advanced reactors should not be specifically developed or built for transforming weapons plutonium into spent fuel, because that aim can be achieved more rapidly, less expensively, and more surely using existing or evolutionary reactor types," Panofsky says.

In line with that reasoning, the Clinton Administration has proposed sharply reduced spending for development of all types of advanced reactors, except for advanced light-water models. In fiscal 1995, funding for the total nuclear energy program at DOE would fall from $343 million to $248 million.

Plutonium's risks to human health depend on its form

In a nuclear explosion, plutonium-239 fissions and releases a huge amount of energy and radiation. But plutonium itself is a highly toxic element that requires a great deal of care in handling.

Experts agree that the silvery, unstable metal plutonium-239, with a half-life of 24,000 years, is hazardous and should be isolated from the biosphere. However, the risks posed to workers and communities by stored plutonium depend on the route of exposure as well as the particle size, isotope, and chemical form.

Weapons-grade plutonium outside the body presents little risk unless exposures are frequent and extensive. It emits primarily alpha particles, which cannot penetrate skin, clothing, or even paper. Nearly all the energy from plutonium is deposited on the outer, nonliving layer of the skin, where it causes no damage. The neutrons and the relatively weak gamma photons it emits can penetrate the body, but large amounts of weapons-grade plutonium would be needed to yield substantial doses.

Workers wearing only lead aprons can handle steel drums containing solid plutonium metal with no immediate untoward effects. However, as weapons-grade plutonium ages, it becomes more dangerous because some of the plutonium-241 it is contaminated with is converted via beta decay to americium-241, which emits far stronger gamma radiation.

On the other hand, plutonium inside the body is highly toxic. Solid plutonium metal is neither easily dispersed nor easily inhaled or absorbed into the body. But if plutonium metal is exposed to air to any degree, it slowly oxidizes to plutonium oxide (PuO_2), which is a powdery, much more dispersible substance. Depending on the particle size, plutonium-239 oxide may lodge deep in the alveoli of the lung where it has a biological half-life of 500 days, and alpha particles from the oxide can cause cancer. Also, fractions of the inhaled plutonium oxide can slowly dissolve, enter the bloodstream, and end up primarily in bone or liver.

Plutonium oxide is weakly soluble in water. If it is ingested in food or water, only a small fraction (4 parts per 10,000) is absorbed into the gastrointestinal tract. However, it may take just a few millionths of a gram to cause cancer over time. In animals, small doses induce cancer, especially in lung and bone.

In published studies of plutonium's effects on humans, most subjects were exposed to multiple sources of radiation. Some researchers say the available health data on plutonium workers have not yet been used to do careful epidemiological studies, because researchers have been denied access to much of the data on workers and military personnel exposed to plutonium. In any event, in the studies done thus far, plutonium workers do not show major excesses of any type of cancer.

Because of the relative lack of human data, the risks from chronic exposure to plutonium are uncertain. Exposure standards in the U.S. are based partly on studies of survivors of Hiroshima and Nagasaki and partly on animal experiments. A 1991 White House Office of Science & Technology Policy study says that "sufficient human data are not available to provide accurate risk assessment of exposure."

Despite evidence of plutonium's toxicity, the Japanese government-owned Power Reactor & Nuclear Fuel Development Corp. (PNC) distributed a video this year that portrays plutonium as harmless. The video was designed to reassure people living near the newly opened Monju breeder reactor, which is fueled with a mixture of plutonium and uranium oxides.

The cartoon features a captivating character called Pluto Boy, a small child with a green cap marked "Pu." Pluto Boy says there is no evidence plutonium causes cancer. "Even if you drink plutonium in your water," he explains, "it won't be absorbed by your stomach and it will be flushed out of your body. ... It is unthinkable that I could cause any adverse effects in the body."

In February, Energy Secretary Hazel O'Leary wrote to PNC, protesting the misleading information presented in the video, and the Japanese media criticized it strongly as well. PNC had already distributed 200 copies of the video to local Japanese authorities, but subsequently promised not to send out any more copies.

However, Sen. J. Bennett Johnston (D.-La.), chairman of the Committee on Energy & Natural Resources and the Appropriations Subcommittee on Energy & Water Development, wants to continue funding the advanced liquid-metal reactor and the modular high-temperature gas-cooled reactor, because "both technologies could consume weapons plutonium more completely than a light-water reactor." He believes the U.S. should consider other policy areas, such as the future need for advanced reactors for electricity generation, when choosing a method of disposing of plutonium. Advanced reactor research may be saved, at least for 1995.

Russian breeder reactors

Analogous to the DOE engineers who want to burn plutonium in advanced reactors are the nuclear experts at Russia's MINATOM who want to burn plutonium in breeder reactors. This group wants to preserve the pits for use in breeder reactors after the government has finished building several large ones. For example, Russian Minister of Atomic Energy Viktor N. Mikhailov predicts, "Fast [breeder] reactors will be ready for large-scale plutonium utilization at the beginning of the next century." And he concludes that "any short-term plutonium management program must be based on safe and reliable storage of weapons plutonium until it can be used in [breeder] reactors." In general, other Russian officials at MINATOM agree with Mikhailov. They say plutonium is a national treasure that should not be mixed with high-level waste. Also, they are adamantly opposed to incorporating the plutonium in mixed-oxide fuel and burning it in ordinary light-water reactors.

Currently, Russia has only one commercial-sized breeder reactor, the BN-600 in Beloyarsk in the Urals, which has been plagued with safety and operating problems. Russia has started site preparation for one large breeder and has drawn up plans for three others, all to be BN-800s and to be built near Chelyabinsk in the Urals. But Russia does not have

the funds to finish them, so the only way it could acquire more breeder reactors in the near future is with heavy subsidies from some other country. It would take 20 to 30 years to build enough breeder reactors in Russia to begin to make a dent in its weapons plutonium, says NAS committtee chairman Holdren.

On the other hand, Richard Wilson, professor of physics at Harvard University, says Russia's schedule for completion of four BN-800 breeder reactors near Chelyabinsk by 2017 may be possible "if we do not confuse matters by insisting to the Russian government that it is a bad idea." Keeping the plutonium secure at Chelyabinsk "is surely easier than keeping it on the tips of thousands of warheads," he adds.

Problems with breeders

The promise of breeder reactors is a significant extension in the life of uranium resources. They permit the gradual replacement of uranium-238 by plutonium-239, which then can fission. But there are several reasons why many nuclear experts outside Russia do not look favorably on the idea of burning weapons-derived plutonium in breeders. One is that it will take several decades before the technology is sufficiently advanced to burn plutonium on a large scale. Another is that under normal operating conditions, the amount of plutonium in the spent fuel from breeders is even greater than in the initial fuel, and the plutonium in the blanket (the uranium-238 surrounding the fuel core) of a breeder is almost ideal weapons grade. Consequently, after burning plutonium in breeders, a nation would have more plutonium than it started with, and there could be a great incentive for terrorist groups to divert the plutonium in the blanket to produce weapons.

Breeder reactors can be modified to produce less plutonium than they are fueled with—in those cases they are called burners. But then, what is usually thought to be their great advantage—creating more fuel in the process of producing electricity—is eliminated. And, "if you redesign the reactor so it doesn't make more plutonium than it is fueled with, you raise new safety issues that have not been adequately resolved," Pigford says.

In addition, most of the breeder reactors built thus far around the world have been plagued with safety problems. Cracks often develop in the heat exchangers and in other parts, and argon gas bubbles passing through the core can cause problems. They contain thousands of tons of circulating sodium and water and large numbers of pipes and valves. Because sodium ignites spontaneously when it contacts water, this system can be safe only if it is entirely leak-proof.

As a consequence of breeder reactors' expense and unreliability, very few Western countries are now interested in developing them. Britain and Germany abandoned research on breeders in 1992, and President Bill Clinton announced last February that the U.S. would no longer fund breeder development. Japan and Russia are the only industrial countries that are actively trying to develop breeder reactor programs.

Storage issues

No one disputes the idea that plutonium pits should be stored securely to eliminate risk of theft or of environmental contamination of the surrounding community. But observers in both the U.S. and Russia see problems with the way their pits currently are stored, and local citizens in both countries who live near storage sites do not want the problems solved by having a permanent, more sophisticated site for pit storage built in their communities.

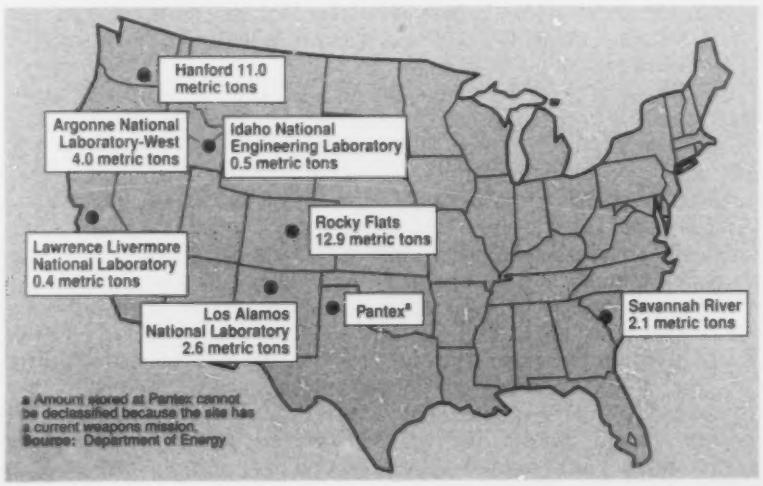
Russian pits are now being kept in warehouses at four sites at Tomsk-7, a formerly secret city near Tomsk, Siberia, and at Chelyabinsk-65, where weapons are being dismantled. Even the Russians admit these storage facilities are unsafe and liable to theft. The facilities do not protect against aircraft crashes, and they do not have an accountancy system even as simple as bar codes to mark the pit containers to enable inspectors to know whether any are missing. Also, they lack portal monitors that record automatically when radioactive materials enter or leave the storage facility. Such monitors were installed on DOE facilities in 1985.

The Pentagon has offered the Russians $30 million to help them establish a better system for accountancy and monitoring, but so far they have not accepted help in this area.

"DOE has developed a lot of systems for material control and accounting," says undersecretary of energy Charles B. Curtis. "The problem is getting Russia to apply these regimes. A team has been in Russia recently trying to do this," he says.

At a cost of $40 million, the U.S. has designed and built about 33,000 safe storage containers for Russian pits, and this summer it will start sending the containers. The U.S. is also providing $90 million for the Russians to design and build a modern underground storage facility for their pits.

Substantial quantities of weapons-grade plutonium are stored at various Department of Energy sites


Hanford 11.0 metric tons
Argonne National Laboratory-West 4.0 metric tons
Idaho National Engineering Laboratory 0.5 metric tons
Rocky Flats 12.9 metric tons
Lawrence Livermore National Laboratory 0.4 metric tons
Los Alamos National Laboratory 2.6 metric tons
Pantex[a]
Savannah River 2.1 metric tons
[a] Amount stored at Pantex cannot be declassified because the site has a current weapons mission.
Source: Department of Energy

The Isaiah project—privatizing plutonium disposal

A consortium of private companies has put forward a proposal for a government-private partnership to use weapons-grade plutonium as mixed-oxide fuel in light-water reactors. Three firms—Battelle Memorial Institute, Newport News Shipbuilding Corp., and Science Applications International Corp.—would acquire two partially completed reactors in Washington State, finish them at their own expense with private financing, and transfer ownership to the U.S. government. They would then operate the reactors to "burn" weapons-grade plutonium and generate electricity. The plan is known as the Isaiah project.

Revenues from the sale of electricity would allow the consortium to repay its debt from finishing the reactors. The government would pay for reactor operations and for fuel fabrication, storage, and disposal. The spent fuel would be stored on the Hanford site until it could be disposed of in a geologic repository.

A Department of Energy facility, built on the Hanford Reservation but never used to produce fuel for the former U.S. breeder program, would make the mixed-oxide fuel for the project. The nuclear reactors proposed for use are Washington Nuclear Project-1 (WNP-1), which is 63% complete and located on the Hanford site, and WNP-3, which is 75% complete and located in Satsop in western Washington. WNP-3 is a System-80 reactor that would not require modification to use a full core of mixed-oxide fuel. WNP-1 would have to be modified.

The project has several advantages. It would gainfully employ two unused reactors. It would confine plutonium burning to two sites, and it would reduce up-front U.S. government costs for plutonium disposal. It would also mean that plutonium burning would be managed by the private sector, which some see as an advantage. WNP-1 and WNP-3 were started at a time when nuclear power was expected to expand rapidly; they were mothballed when the owner decided that power from these reactors would not be needed.

"The Isaiah project could tip the balance in favor of burning mixed-oxide fuel in reactors because it is a convenient institutional arrangement," says Robert J. Budnitz, president of Future Resources Associates in Berkeley, Calif. However, if the Clinton Administration waits until 1996 to make a decision on plutonium disposition, as it plans to do, two of the leading light-water reactor options—WNP-1 and WNP-3—may no longer be available. Their current owner plans to begin dismantling them early next year.

The new facility will have temperature control, modern alarms, a fire-control system, and will provide protection against aircraft crashes.

The Russian government may itself finance construction of a second storage facility at Chelyabinsk-65. Site preparation for the U.S.-funded facility will begin this summer at Tomsk-7, and it is scheduled to be finished in 1997.

Groundwater levels at the proposed sites are high, and Russians living nearby are concerned that plutonium will pollute the groundwater in their areas or that whatever is done with the pits in the future will contaminate the groundwater. Also, they fear that what started out as a storage site will end up as a site where plutonium is used to feed breeder reactors, says William H. Mitchell of the Nuclear Safety Campaign, a Seattle-based organization that works on issues related to the nuclear weapons complex.

All U.S. pits from dismantled weapons are being stored at the DOE Pantex plant near Amarillo. They are kept in 16 World War II-era concrete earth-covered bunkers called magazines. These have no electricity, climate control, or sprinkler systems. Physical barriers like the steel door, 2,500-lb concrete blocks in front of the door, and the heavy guard around the facility provide deterrents against theft. Workers wearing lead aprons place the metal barrels holding pits on the floor of the bunkers, but soon a shielded forklift will be used for this purpose. However, the very simplicity of the bunkers means little can go wrong with them. "Once you lock up a pit in a container inside a magazine," says Gerald Johnson, plant manager at Pantex, "the only accident scenario that was identified as a potential credible accident is an aircraft crash into one of the magazines." On the other hand, he does say that "if we build a new facility for the Russians, perhaps we should build one for the U.S. as well."

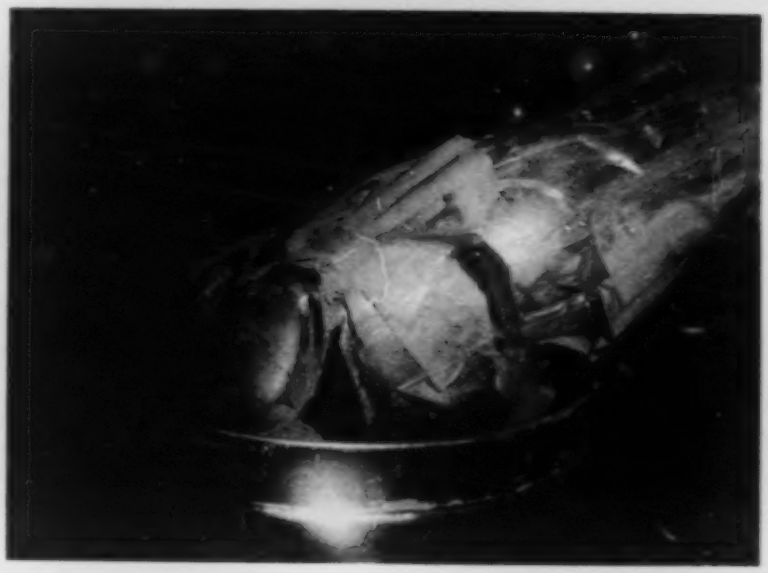
There are about 140,000 aircraft flights over Pantex each year. Most of the commercial flights are at high altitude, but military planes training at the Amarillo airport fly over relatively low. "We are working with the Department of Defense and the city of Amarillo to see if there is a way to restrict or reduce the number of military flights over Pantex," Johnson says. The containers used to store the pits are inferior to the ones the U.S is supplying Russia. But the U.S. will soon begin using a similar container, which will largely protect the plutonium in the event of an airplane crash.

The citizens who live near Pantex do not oppose disarmament. They are concerned, however, that if a more modern storage facility is built at Pantex and all of the pits are stored there, the pits will remain there for many decades. They are also concerned about groundwater contamination with plutonium in the event of an aircraft accident. Pantex sits on top of an upper aquifer at a depth of about 250 feet and the Ogallala aquifer 400 to 450 feet below the surface. Low levels of volatile organic compounds have shown up in the upper aquifer.

Beverly Gattis, head of the Amarillo citizens group Serious Texans Against Nuclear Dumping (STAND), wants DOE to seriously consider using sites other than Pantex for storing at least some of the pits. She says her group is very aware of environmental problems at many DOE sites and continues to be concerned about problems at Pantex because the "regulatory and bureaucratic structure that created the problems is still largely intact." Doris B. Smith, chairwoman of Panhandle Area Neighbors & Landowners, Amarillo, says storing plutonium from weapons and possibly processing that plutonium could be the greatest environmental risk ever posed to the area's agricultural-based economy.

Because of opposition of groups like STAND, DOE reached an agreement with the state of Texas promising to store a total of no more than 12,000 pits at Pantex over the next three years. Currently, about 5,000 to 6,000 pits from

Plutonium storage containers aren't fail-proof



Two nested plutonium storage vessels that originally held 2.5 kg of pure plutonium metal failed at Los Alamos National Laboratory in New Mexico in November 1993. Over a period of seven to 10 years, much of the plutonium was oxidized to plutonium oxide (PuO_2), expanding in the process and rupturing the inner storage vessel.

Originally, the plutonium had been placed in a metal tube with improperly welded caps. The tube was then covered with a polyethylene bag, sealed with tape, and placed in another, larger, metal container with a slip lid. Neither metal container was hermetically sealed.

Apparently, plutonium oxidation occurred in two stages. First, over a period of five to 10 years, fine particles of plutonium oxide were transported by thermal currents through openings in the inner vessel to the surrounding plastic bag. These caused radiolytic decay of the plastic releasing hydrogen, which moved into the inner vessel and reacted with plutonium to form plutonium hydride. Eventually, the embrittled plastic bag failed completely, exposing the plutonium in the inner container to the air in the outer vessel.

In the second stage, oxidation proceeded very rapidly because it was catalyzed by plutonium hydride. The free volume of the inner vessel was filled with plutonium oxide, which has a volume about 40% greater than that of pure plutonium, until the inner vessel ruptured. From that point, the reaction proceeded even more rapidly. If the process had gone on long enough, the oxide would have ruptured the outer container as well.

The container at Los Alamos contaminated workers' clothing as they removed it from a vault, but the workers did not absorb any of the plutonium oxide, and none of it was dispersed to the environment.

A similar incident occurred in a facility in the U.K. There, plutonium oxide ruptured both the inner and outer containers and released oxide to the shelves where the metal was stored.

In December 1993, the Department of Energy (DOE) sent out an advisory to its labs and facilities warning that all plutonium containers should be inspected periodically to determine whether the plutonium is undergoing rapid oxidation. Also, before handling, plutonium packages should be taped or placed in plastic bags to reduce the possibility of venting oxide to the air, DOE says. Currently, DOE is inventorying the plutonium at its facilities and, at the same time, determining how well it is stored.

Much of the plutonium that is not in weapons components is likely to be stored with plastic at DOE facilities. "All of this material at this point has to be considered suspect," says Joseph C. Martz of the nuclear materials technology division at Los Alamos National Laboratory. "Much of it is stored in uncharacterized containers."

the weapons dismantlement program are kept there, and by 2003, a total of about 20,000 pits will need storage at Pantex or at some other site.

At DOE, an agencywide group led by Robert W. DeGrasse Jr. is preparing what is called a programmatic environmental impact statement. It will analyze the environmental impacts of plutonium pit storage at Pantex and at other potential sites, including military bases. It will also assess the affects of the many different proposals for plutonium disposal, including those recommended by NAS. As a part of this effort, an implementation plan will be finished by fall, and DOE will make a final recommendation on plutonium disposition in 1996.

An interagency working group chaired by Frank von Hippel of OSTP is attempting to ensure that all of the relevant agencies—including the Defense Department, State Department, and Environmental Protection Agency—are listened to on the issue of plutonium storage and disposition. Von Hippel's group also forms the U.S. side of a joint U.S.-Russian working group that is trying to find a way to provide safe and secure storage of Russian fissile materials to guard against theft and hijacking.

Plutonium not in pit form

Weapons-grade plutonium is stored at 43 DOE sites in many forms other than pits. Excluding plutonium-containing waste, plutonium is kept as pits, pure metal, oxide, scrap, and nitrate and other solutions. In some ways, the plutonium in these other forms, which totals about 33.5 metric tons, presents more of a proliferation risk than do the pits because it is scattered across many facilities that are less well guarded than Pantex, and some of it is not packaged or inventoried well. For example, much of the plutonium is stored in an inner metal container, sealed inside a plastic

bag, and that assembly is placed in an outer metal container. If small leaks develop in the containers, and often these are not hermetically sealed, radiolytic decay of the plastic can release hydrogen that can catalyze rapid oxidation of the plutonium. Plutonium oxide has a greater volume than plutonium, so this reaction can cause the containers to break and contaminate storage areas with the radioactive oxide.

In March, DOE began a nationwide review of its vulnerabilities in storing and handling plutonium. The purpose of the review is to inventory weapons plutonium at DOE facilities and to check for "conditions or weaknesses that could lead to unnecessary increased radiation exposure of workers, release of radioactive materials to the environment, or radiation exposure to the public."

Last month, analysts at the Natural Resources Defense Council announced a discrepancy of 1.5 metric tons between their calculation of total weapons-grade plutonium production and the 89 metric tons Energy Secretary Hazel R. O'Leary announced in December. The 1.5 metric tons, though a small portion of total production, is enough to make 300 nuclear weapons.

DOE admits that there are discrepancies in its plutonium accounting, but says these are mostly the result of technical and paperwork problems. The vulnerability study, which is slated to be finished Sept. 30, will establish a more accurate inventory of the material.

CONFERENCE UPDATE

S•E•C•O•N•D
INTERNATIONAL CONFERENCE
AND EXHIBITION ON

Chemistry in Industry

State of Bahrain
October 24-26, 1994

Highlights

- 250 papers will be presented.
- 160 Exhibitors from 27 countries will be participating in the conjugate exhibition
(More space is available)

Session Topics

- Process and Refining Chemistry
- Environmental Chemistry
- Petroleum Technology
- Oil Field Chemistry
- General Chemistry
- Geochemistry

SAICSC-ACS
P.O. Box 1723
Dhahran 31311
Saudi Arabia
FAX: (966-3) 873-7766

Bilateral arrangements

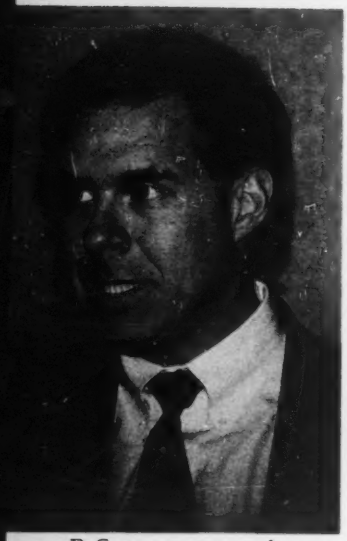
In addition to providing storage containers and funds for a storage facility for Russian pits, the U.S. has made a number of bilateral arrangements with Russia to help stem the spread of nuclear materials. At their Jan. 14 summit meeting, President Clinton and President Boris Yeltsin agreed to nonproliferation goals. On March 16, O'Leary and Russian Minister of Atomic Energy Mikhailov signed an agreement that will permit mutual inspection of plutonium storage facilities. Russian inspectors will be allowed into the Pantex facility, and U.S. inspectors will be allowed to inspect plutonium facilities at Tomsk. Neither side will be permitted to see the actual pits because that would give away sensitive weapons design information. But they will take radiation measurements of the containers that will reveal whether pits are stored there. The details of the inspections haven't been worked out.

In another pact, Russia has agreed to shut down its three remaining reactors that produce plutonium for weapons and also generate power for the cities of Tomsk and Krasnoyarsk, by 2000, when alternative power sources will have been built. In return, the U.S. will help Russia obtain financing for alternative power plants. In the meantime, Russia will continue to separate weapons-grade plutonium from the spent fuel from these reactors, but has promised not to use the plutonium in new weapons. It says it has no storage space for the aluminum-clad fuel rods and that they will corrode if not reprocessed.

The U.S. has promised to put its surplus stocks of highly enriched uranium and plutonium under inspection by the International Atomic Energy Agency and is now in the process of deciding what stocks are surplus. The Nuclear Weapons Council, a group composed of representatives from DOD, DOE, and the Joint Chiefs of Staff, has made an initial decision that is now under review. Also, the U.S. has pledged to produce no more weapons-grade plutonium or highly enriched uranium. Facilities that manufacture these materials have been shut down for a number of years.

In addition, the U.S. has promised to be much more open in most of its policies regarding plutonium. As a part of this new openness, O'Leary announced that the total U.S. production of weapons-grade plutonium was 89 metric tons and supplied a list of the major amounts of plutonium that are stored at various DOE sites. The purpose of the new openness is twofold. One goal is to gain trust and eventually public acceptance in the U.S. for whatever is done to dispose of plutonium. The other is to set an example

Gattis: pit storage raises environmental concerns



DeGrasse: openness advances nonproliferation efforts

for Russia and the rest of the world.

If the U.S. does not share certain information about its plutonium and reveal enough data to show it is actually dismantling as many weapons as it says it is, Russia will probably not reveal enough evidence to demonstrate that it is keeping its word. According to DeGrasse, "Openness advances U.S. nonproliferation efforts" and helps build public confidence in DOE, whose reputation is now at a low level. "DOE will find it is much more capable of achieving its goals if it can be trusted," he says.

No consensus

Because the White House generally favors one of the NAS disposal options and the majority of Russian government officials are determined to save their plutonium for use in breeder reactors, many observers believe the U.S. and Russia will not agree on the ultimate disposition of plutonium for many years to come. A Pentagon official says, "I really don't see any basis for agreement between the U.S. and Russia on ultimate disposition." There is nothing pushing them to make a choice, so "it's a decision that probably won't be made for 20 years, 10 years at the earliest," he adds. "Everyone can agree plutonium ought to be stored safely and securely. No one is going to agree on what to do next."

Mitchell of the Nuclear Safety Campaign echoes that view: "We just don't know how to proceed with the Russians, aside from the storage issue." The U.S. could go ahead unilaterally and destroy most of its plutonium while Russia stores its pits intact, but this would be entirely unacceptable politically.

Robert H. Socolow, director of the Center for Energy & Environmental Studies at Princeton University, sums up the current tension surrounding the first steps toward nuclear disengagement: "The production of nuclear weapons ... has demanded single-minded dedication, isolation, and risks to personal safety on the part of individuals; sustained commitment on the part of political leadership; and large expenditures of public funds. Since 1945, no nuclear weapons have been used in war; they have 'kept the peace.'

"Small wonder, then, that those involved see themselves and their colleagues as unsung heroes and can only slowly comprehend that the time has come to undo all their work. Reversing the nuclear arms race will take tremendous political will in every country that has invested heavily in nuclear weapons. Rendering unusable for weapons the plutonium and highly enriched uranium that have been loved into existence will require a worldwide cultural shift. Yet, the alternative is a nuclear arms race that spreads throughout the world, and, eventually, nuclear wars from miscalculation or malfunction, with untold horror." □

2-Propen-1-ol/Vinyl Carbinol

Versatile starting material for a variety of specialty monomers and polymers

Applications

Opthamalic prescription lenses
Safety glasses and safety shields
Antiglare CRT screens
Architectural, water-based and radiation-curable coatings
Epoxy fiberglass, glass fiber and fiber/resin compositions

New Mini-Bulk™ Sizes

Available in 90, 200 and 400 liter cylinders

To Order

Allyl alcohol or to receive a product information bulletin and for more information about SAF's new Mini-Bulk™ program call or fax:

TEL: 800-336-9719
FAX: 800-368-4661

SAF®
BULK CHEMICALS
(the power of three)
Sigma, Aldrich, Fluka Chemical Companies

Manufactured By:

ARCO Chemical Company

CIRCLE 4 ON READER SERVICE CARD